High-energy hadron physics at J-PARC

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Abstract. The J-PARC facility is near completion and experiments will start in 2009 on nuclear and particle physics projects. In this article, the J-PARC facility is introduced, and possible projects are discussed in high-energy hadron physics by using the primary proton beam of 30−50 GeV. There are proposed experiments on charm-production and Drell-Yan processes as well as single spin asymmetries for investigating quark and gluon structure of the nucleon and nuclei. Parton-energy loss could be studied in the Drell-Yan processes. There is also a proposal on hadron-mass modifications in a nuclear medium by using the proton beam. In addition, possible topics include transition from hadron to quark degrees of freedom by elastic pp scattering, color transparency by $(p,2p)$, short-range correlation in nuclear force by $(p,2pN)$, tensor structure functions for spin-one hadrons, fragmentation functions, and generalized parton distributions in the ERBL region although proposals are not written on these projects. If proton-beam polarization is attained, it is possible to investigate details of nucleon spin structure. In the last part of this article, our own studies are explained on parton distribution functions in connection with the J-PARC projects.

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INTRODUCTION

The J-PARC stands for the Japan Proton Accelerator Research Complex, and it is located at Tokai in Japan [1]. It is a joint facility between JAEA (Japan Atomic Energy Agency) and KEK (High Energy Accelerator Research Organization) for projects in various fields of science. The J-PARC provides most intense proton beam in the multi-GeV energy region. Nuclear and particle physics projects use secondary beams such as kaons, pions, and neutrinos as well as the primary 50-GeV proton beam. The construction is near completion and experiments will start soon. The first nuclear and particle physics experiments are on strangeness nuclear physics and neutrino oscillation.

As future hadron experiments, there are many possibilities. It is the purpose of this paper to introduce "possible" high-energy hadron projects by using the primary proton beam of 30−50 GeV rather than to explain approved hadron experiments with kaon and pion beams. It is possible to investigate various aspects of hadron and nuclear structure by using the proton beam. They include clarification of flavor-dependent antiquark distributions at large Bjorken x and nucleon spin structure. The J-PARC facility is expected to play a major role in the studies of hadron structure and hadronic many-body systems in a different kinematical region from RHIC and LHC.

This article consists of the following. First, the J-PARC facility is introduced. Then, we explain possible hadron-physics projects with the 30−50 GeV proton beam. In the last part, our studies on the parton distribution functions and fragmentation functions are discussed in connection with possible J-PARC projects. Finally, a summary is given.

J-PARC FACILITY

The J-PARC accelerator consists of a linac as an injector, a 3-GeV rapid cycling synchrotron, and a 50-GeV synchrotron as shown in Fig. 1 [1]. The J-PARC provides most intense proton beam in the high-energy region ($E > 1$ GeV). Other proton accelerators have a beam power less than 0.1 MW, whereas the J-PARC expects to have 1 MW in the 3-GeV synchrotron and 0.75 MW in the 50-GeV one. The J-PARC has three major projects: (1) material and life sciences with neutrons and muons produced by the 3-GeV proton beam, (2) nuclear and particle physics with secondary beams (pions, kaons, neutrinos, and so on) by the 50-GeV proton beam and also with protons of the 50-GeV primary beam, (3) nuclear transmutation by the linac.

Figure 1: Bird's eye view of the J-PARC facility [1].

Nuclear and hadron-physics experiments will be done at the hadron experimental facility in Fig. 1 [1, 2, 3]. We should mention that there are also hadron topics on neutrino interactions with the nucleon and nuclei. In this article, we discuss high-energy hadron projects in the hadron hall, for which a beam-layout plan is shown in Fig. 2. The K1.8 is the first beamline which will be completed. It is intended to have kaons with momentum around 1.8 GeV/c for the studies on strangeness -2 hypernuclei with Ξ^- by (K^-, K^+) reactions. The K1.1/0.8 beamline is designed for low-momentum stopped kaon experiments such as the studies of kaonic nuclei. The neutral kaon beamline (KL) is for studying CP violating processes such as $K_L \to \pi^0 \nu \bar{\nu}$. The "High p" in Fig. 2 indicates the high-momentum beamline for 50-GeV protons. In the beginning stage of J-PARC, the proton beam energy is 30 GeV instead of the designed 50 GeV. At a later stage, we expect to have 50 GeV energy recovery.

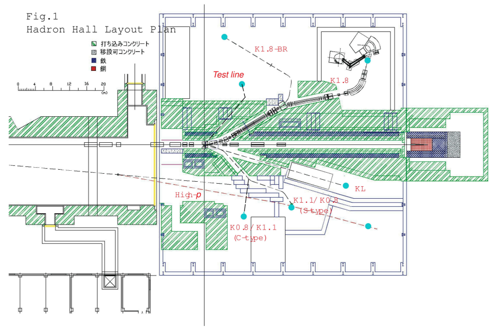

Figure 2: Layout of the hadron hall [1].

HADRON PHYSICS WITH PRIMARY PROTON BEAM

There are opportunities to investigate hadron and nuclear structure at high energies by using the high-momentum beamline in Fig. 2 [3, 4]. There are proposals on hadron-mass modifications in a nuclear medium, Drell-Yan and charm-production processes, single spin asymmetries, elastic scattering, and high-energy spin physics with proton-beam polarization [2]. In the following discussions, additional topics are explained at the primary proton beamline from the author's personal point of view without restricting ourselves to the proposed experiments.

There are two types of topics: (1) structure functions and related physics (quark and gluon physics) and (2) hadronic aspects.

First, the structure functions have both aspects of nonperturbative and perturbative quantum chromodynamics (QCD). In order to obtain information about internal structure of hadrons, one needs to subtract out the perturbative QCD part from cross sections. In order to obtain reliable results for the nonperturbative part, higher-order QCD corrections need to be understood. It is known that such corrections, which are expressed by "K factors", are large in fixed-target experiments. In particular, the center-of-mass energy is relatively low: $\sqrt{s}$ =8 GeV in the beginning and 10 GeV later at the J-PARC. It means that careful estimations are necessary for the pQCD (perturbative QCD) corrections. Fortunately, there are significant developments in the recent years on resummations of soft-gluon radiations which give rise to large corrections at low energies. It is shown in Ref. [5] that the pQCD corrections converge if the resummations are properly taken into account at $\sqrt{s} = 10$ GeV in the Drell-Yan processes. It means that Drell-Yan measurements are valuable for extracting information on various parton distribution functions (PDFs) because the perturbative part is theoretically under control. For charm-production processes, we still need theoretical studies on such corrections [6]. Conversely, the large corrections mean that J-PARC measurements are challenging and interesting for pQCD physicists in testing their high-order calculations.

Second, there are also interesting hadronic topics other than the structure functions and related topics. These projects could be appropriate especially at the 30 GeV energy. Possible projects include hadron masses in a nuclear medium, transition from hadron degrees of freedom to quark ones by elastic pp scattering, color transparency in $(p,2p)$ reactions, short-range correlation in nuclear force by $(p,2pN)$ reactions, and generalized parton distributions (GPDs). These topics are explained in the following.

Partonic structure with primary proton beam

Drell-Yan processes

Drell-Yan ($pp \to \mu^+\mu^- X$) measurements are important in establishing unpolarized PDFs, especially antiquark distributions at medium x [7]. For example, the Fermilab-E866 measurements in Fig. 3 played a key role in finding flavor asymmetric antiquark distributions ($\bar{u} \neq \bar{d}$). They lead to investigations on a nontrivial aspect of nucleon structure [8], and physics mechanism could be related to peripheral structure of the nucleon such as pion clouds. The expected measurements by the Fermilab-E906 and J-PARC (50 GeV) extend the x region to larger x ($x_{max} \sim 0.6$) [2], where the E866 measurements did not probe. On the other hand, it is necessary to investigate possible mechanisms theoretically to create the difference $\bar{u} \neq \bar{d}$ at $x > 0.2$.

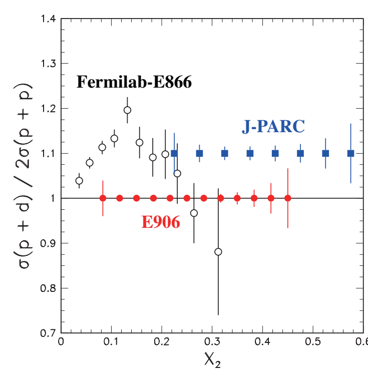

Figure 3: Drell-Yan cross section ratio $\sigma(p+d)/\sigma(p+p)$ [2].

Charmed-meson productions

The proton energy is 30 GeV at the initial stage, and it could be too low to investigate the Drell-Yan process. One of possible projects with the 30-GeV beam is to study J/ψ and open-charm production processes [2, 6]. The J/ψ production has been discussed

as a possible signature of quark-gluon plasma (QGP) in heavy-ion physics, so that it is important to understand its production mechanism. Furthermore, the J/ψ and open-charm production processes probe the gluon distributions in the nucleon and nuclei. We should note that the gluon distribution in the nucleon is not determined at large x (> 0.3), and it is a major obstacle for finding new physics by high-p_T jet events in hadron colliders. The J-PARC is a large-x facility which contributes to the PDF determination at large x if a theoretical description is established for the charmed-meson productions.

Parton energy loss

Recently, parton energy loss became a hot topic in heavy-ion reactions because it is related to a QGP formation by suppression of high-p_T mesons. There is also a development on this topic by the AdS/CFT correspondence. In order to discuss QGP properties, it is necessary to describe the energy loss properly and to test it in an independent experiment. The Drell-Yan processes with nuclear targets provide a clean method to investigate the quark energy loss in a cold nuclear medium. The energy loss gives rise to nuclear modifications of quark momentum distributions before a $q\bar{q}$ annihilation, which results in changes of Drell-Yan cross sections [2].

Single spin asymmetries

Single spin asymmetries (SSAs) can be investigated without proton-beam polarization. For example, the SSA for D-meson production has been estimated for the J-PARC in Fig. 4 [2, 9]. Here, the asymmetry could be related to Sivers functions, which describe unpolarized quarks in the transversely polarized nucleon, and they are related to angular momenta of quarks. It is important to note that J-PARC measurements are sensitive to quark Sivers effects, whereas RHIC ones are to gluon Sivers effects. The Sivers functions can be also investigated by SSAs in the $p\vec{p}$ Drell-Yan process. If a target is transversely polarized, transversity distributions and Boer-Mulders functions could be also measured by the SSA in the Drell-Yan [2]. The SSA in pp elastic scattering was proposed as a possible experiment to investigate more details of observed anomalous asymmetries in the p_T ~6 GeV region at CERN and BNL by extending the measurements to $p_T = 12$ GeV at J-PARC [2].

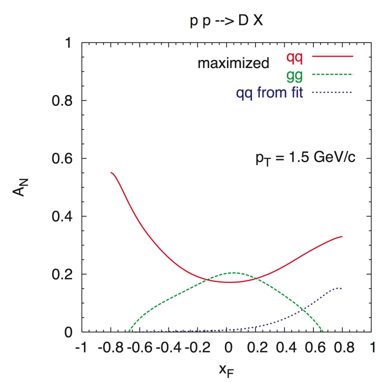

Figure 4: Single spin asymmetry for D-meson production [2].

Tensor structure functions for spin-one hadrons

There exist new polarized structure functions for spin-1 hadrons due to their tensor structure nature. There are few experimental studies on them although spin structure of the spin-1/2 nucleon has been investigated extensively. At J-PARC without the proton polarization, tensor polarized distribution functions can be measured by proton-deuteron Drell-Yan processes with a polarized deuteron target [10]. The tensor structure functions are known as b_1 and b_2 in the leading twist, and the first measurement was reported by the HERMES collaboration in 2005 [11]. However, experimental errors are large for discussing x dependence. The $p\vec{d}$ Drell-Yan measurements at J-PARC have an advantage over the HERMES and future lepton-scattering measurements because antiquark tensor

distributions can be measured for the first time and a sum rule $\int dx b_1(x) = 0$ could be studied experimentally [10, 11]. Theoretically, we need to investigate mechanisms to create the tensor polarization in the quark level.

Fragmentation functions

Recently, semi-inclusive reactions became important for investigating nucleon structure and properties of quark-hadron matters. In describing hadron-production processes, fragmentation functions are necessary. A fragmentation function $D_i^h(z)$ indicates the probability to produce a hadron h from a parton i with the energy ratio $z = E_h/E_i$. They have been determined mainly by hadron-production cross sections in e^+e^- annihilation. However, the gluon function has a large uncertainty [12], which makes it difficult to reliably discuss any hadron-production cross sections in pp and pA. In hadron productions at J-PARC, cross sections are dominated by gluon-gluon interaction processes, so that they could be suitable for determining the gluon fragmentation function at large z (~ 1).

Hadronic structure with primary proton beam

We have introduced possible J-PARC projects on partonic structure of hadrons. At 30 GeV, perturbative corrections are generally large, so that there are possibilities that partonic interpretations are difficult for some cross sections. In the following, a few ideas are given on hadronic projects which are possible at both 30 and 50 GeV energies although actual proposals have not been submitted yet except for the mass modification.

Hadron-mass modifications in nuclear medium

Chiral symmetry could play an important role in generating hadron masses because current quark masses are much smaller than hadron masses. Chiral symmetry breaking leads to a finite quark condensate, which is reflected as hadron-mass modifications in a nuclear medium. It was proposed to measure the mass modifications of vector mesons (ρ, ω, ϕ) [2]. The modifications are theoretically expected due to partial restoration of the chiral symmetry. For example, recent KEK-E325 experimental results indicated a 9% mass shift for ρ and ω. Much accurate data will be obtained at J-PARC, so that the chiral dynamics will become clear in nuclei.

Transition from hadron to quark degrees of freedom

Cross sections for hadron reactions are described by hadron degrees of freedom (d.o.f.), baryons and mesons, at low energies, whereas they should be described by quark d.o.f. at high energies. It is possible to investigate the transition from hadron to quark d.o.f. by measuring pp elastic cross sections at various proton energies. In the high energy limit, the elastic cross section should be described by gluon exchanges between constituent quarks, which gives rise to a counting rule: $d\sigma/dt \sim s^{2-n} f(\theta_{c.m.})$ where n is the total number of interacting elementary particles. This transition from hadron to quark d.o.f. has been observed in $\gamma p \to \pi^+ n$ at $\sqrt{s} \sim$2.5 GeV [13]. Similar studies could be done for the pp scattering at J-PARC.

Short-range correlation in nuclear force

Nuclear force has been investigated in terms of one-boson-exchange processes and

also by effective quark models. Direct relation to QCD is now being studied due to development of lattice QCD. Short-range repulsion exists within the distance $r \sim$0.4 fm, and it is especially important for saturation properties of nuclei. There is an interesting experimental development on isospin dependence of the short-range correlation recently. The BNL experiment $A(p,2pN)X$ and JLab one $A(e,e')X$ at $x > 1$ indicated that *pn* short-range correlation is twenty times larger than the *pp* one [14]. The tensor force seems to play an important role in the short range; however, this unexpected result needs to be explained theoretically. On the other hand, this result leads to a modification of neutron-star structure because a certain fraction of protons exist in the star. It should be possible to measure the $A(p,2pN)X$ reaction with better accuracy and with higher proton momentum (namely shorter range) at J-PARC.

Color transparency

At large momentum transfer, a small-size component of the hadron wave function should dominate in hadron cross sections. This small-size hadron could pass freely through a nuclear medium, which is called color transparency. At J-PARC, the $(p,2p)$ reaction could be investigated for a nuclear target. Nuclear transparency T is defined by the cross-section ratio to the nucleonic one: $T = \sigma_A/(A\sigma_N)$. As the hard scale (energy of the proton) becomes larger, namely as the hadron size becomes smaller, the nuclear transparency should increase. Such measurements were done at BNL up to the proton momentum 14 GeV/c [15]. The data indicated an interesting turnover at $p \simeq 9$ GeV/c. First, we need to establish a theoretical model to explain the BNL results, and then measurements could be extended to $30-50$ GeV/c region at J-PARC for further studies.

Generalized parton distributions

Generalized parton distributions (GPDs) contain global information on the nucleon structure from low to high-energy region. The GPDs become PDFs in the forward limit ($\xi = t = 0$), where t is momentum transfer squared and ξ is a skewdness parameter. The first moments, namely the GPDs integrated over x, are form factors, and second moments are angular momenta of quarks. The second moments are especially important because contributions of angular momenta could solve the nucleon spin issue. The GPDs have been measured in lepton scattering; however, they could be also investigated by proton reactions in the ERBL (Efremov-Radyushkin-Brodsky-Lepage) region $-\xi < x < \xi$. We may investigate *e.g.* $pp \to pn\pi$ and $pp \to p\Delta\pi$ for measuring nucleonic and $N \to \Delta$ transition GPDs at J-PARC. A theoretical formalism is now being developed for such processes by using the $30-50$ GeV proton beam [16].

Spin physics with proton beam polarization

Feasibility studies indicated that the primary proton beam can be polarized at J-PARC [2]. By double spin asymmetry experiments, the details of nucleon spin structure should be investigated. As shown in Fig. 3, the J-PARC probes the large-x region ($x > 0.2$). If the proton-beam polarization is attained, it is a complementary project to the RHIC-Spin in investigating a different kinematical region. The RHIC measurements are generally sensitive to the smaller-x region.

Flavor dependence of the antiquark distributions, $\bar{u}$ and $\bar{d}$, has been investigated by

E866 as shown in Fig. 3. Flavor dependence of the polarized antiquark distributions is scarcely known although there are some hints from semi-inclusive DIS experiments for pion and kaon productions. J-PARC Drell-Yan measurements on the double-spin asymmetry should be able to clearly answer the antiquark flavor dependence ($\Delta\bar{u}/\Delta\bar{d}$) at $x > 0.2$. It is important for establishing the origin of nucleon spin and for testing models of producing the flavor asymmetric antiquark distributions. In addition, double spin asymmetry measurements are possible for hadron (π, J/ψ, ...) and direct-photon productions. These measurements should lead to a complete understanding of the nucleon spin from small x to large x together with measurements at other facilities.

PARTONIC STRUCTURE OF NUCLEON AND NUCLEI

In this last part of this article, our own studies are discussed on the PDFs in the nucleon and nuclei in connection with the J-PARC projects.

First, we have been investigating optimum nuclear PDFs by analyzing world data on structure function F_2 and Drell-Yan cross sections for nuclei. In Fig. 5, the current situation is shown for nuclear modifications of the PDFs in the calcium nucleus at Q^2=10 GeV^2 [12]. The uncertainties are shown by the shaded bands. We notice that antiquark distributions at $x > 0.2$ and gluon distributions are not determined. By the Drell-Yan and charm-production processes at J-PARC, we should be able to determine the antiquark distributions at $x > 0.2$ and possibly also gluon distributions.

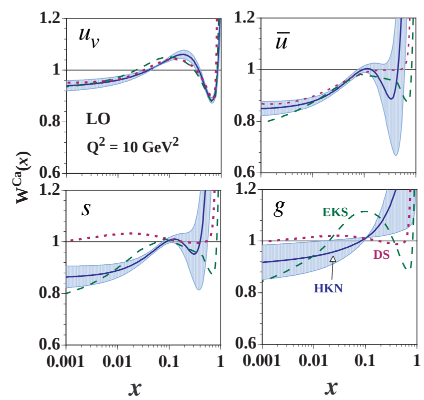

Figure 5: Nuclear modifications of PDFs [12].

Second, the situation of the polarized PDFs is shown in Fig. 6 [12]. The distributions are not well determined in the polarized antiquark and gluon distributions. Especially, the gluon distribution has a large uncertainty band, which is one of the reasons why the origin of the nucleon spin is not clarified. If the proton-beam polarization is attained at J-PARC in future, these distributions can be investigated by the double spin asymmetries in Drell-Yan and hadron-production processes.

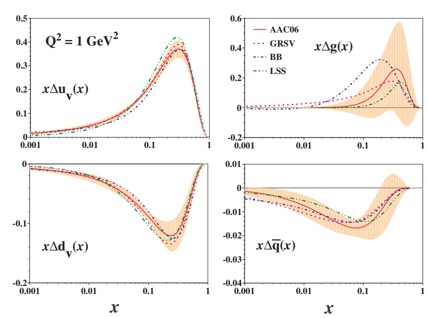

Figure 6: Polarized PDFs [12].

Third, fragmentation functions (FFs) could be investigated by hadron-production processes at J-PARC. The FFs have been determined mainly by hadron productions in e^+e^- annihilation. We found in Ref. [12] that gluon and light-quark FFs have large uncertainties. The gluon function should be determined by hadron facilities such as RHIC, LHC, and J-PARC because gluon subprocesses dominate the small-p_T part of hadron-production cross sections. In particular, the lower-energy J-PARC probes the very large-z region ($z \sim 1$), so that measurements should be important for establishing fragmentation processes from a gluon.

SUMMARY

The hadron-physics experiments will start at J-PARC in 2009, and they are important for new developments in hadron and nuclear physics. The first project is on new many-body systems with strangeness by using pion and kaon beams. In this article, we focused on other hadron-physics projects at high energies by using the $30-50$ GeV primary proton beam.

The proposed Drell-Yan and charm-production experiments are valuable for clarifying the flavor dependence of antiquark distributions in the nucleon at $x > 0.2$, nuclear antiquark distributions, and possibly also the gluon distributions at large x in the nucleon and nuclei. The parton-energy loss can be studied in the Drell-Yan. From single spin asymmetry measurements, it could be possible to learn about orbital angular momentum contributions to the nucleon spin. It is important to measure mass modifications of vector mesons in a nuclear medium for investigating chiral dynamics. There are other interesting projects in addition to these proposed experiments. They include new spin-1 structure, fragmentation functions, transition from hadron to quark d.o.f., short-range correlation in nuclear force, color transparency, and GPDs. If the proton beam is polarized, nucleon spin structure can be studied in details, for example, on the flavor dependence of polarized antiquark distributions. In the last part, we explained the current status of the PDFs and fragmentation functions, which are related to the J-PARC projects, by global analyses of experimental data. The J-PARC will be one of leading facilities in hadron and nuclear physics.

REFERENCES

1. http://j-parc.jp/index-e.html. S. Sawada, Nucl. Phys. **A782**, 434 (2007).
2. http://www.j-parc.jp/NuclPart/Proposal_e.html. High-energy hadron projects are in the proposals: P04, J. Chiba *et al.* (2006); P23, A. W. Chao *et al.* (2007); P24, M. Bai *et al.* (2007). The proposal on the mass modification is P16, S. Yokkaichi *et al.* (2006).
3. S. Kumano, Nucl. Phys. **A782**, 442 (2007). For overview talks on hadron physics at J-PARC, see http://www.pg.infn.it/hadronic06/; http://inwpent5.ugent.be/workshop07/; http://j-parc.jp/NP08/.
4. For possible topics on hadron physics at J-PARC, see slides at http://www-conf.kek.jp/J-PARC-HS05 /program.html; http://www-conf.kek.jp/NP_JPARC/program.html; http://j-parc.jp/NP08/.
5. H. Yokoya and W. Vogelsang, hep-ph/0607043, pp. 723-736 in Proceedings of 14th International Workshop on Deep Inelastic Scattering, World Scientific (2007).
6. J.-W. Qiu, talk at this workshop, http://cdsagenda5.ictp.trieste.it/full_display.php?email=0&ida=a07151; M. Stratmann in http://www-conf.kek.jp/hadron08/hehp-jparc/.
7. J.-C. Peng, talk at this workshop, arXiv:0807.3538 [nucl-ex].
8. S. Kumano, Phys. Rept. **303**, 183 (1998); G. T. Garvey and J.-C. Peng, Prog. Part. Nucl. Phys. **47**, 203 (2001).
9. M. Anselmino *et al.*, Phys. Rev. D **70**, 074025 (2004).
10. S. Hino and S. Kumano, Phys. Rev. D **59**, 094026 (1999); D **60**, 054018 (1999); F. E. Close and S. Kumano, Phys. Rev. D **42**, 2377 (1990).
11. A. Airapetian *et al.*, Phys. Rev. Lett. **95**, 242001 (2005).
12. M. Hirai *et al.*, Phys. Rev. D **75**, 094009 (2007); C **76**, 065207 (2007); D **74**, 014015 (2006).
13. L. Y. Zhu *et al.*, Phys. Rev. Lett. **91**, 022003 (2003).
14. E. Piasetzky *et al.*, Phys. Rev. Lett. **97**, 162504 (2006); R. Shneor *et al.*, Phys. Rev. Lett. **99**, 072501 (2007).
15. J. Aclander *et al.*, Phys. Rev. C **70**, 015208 (2004).
16. S. Kumano, M. Strikman, and K. Sudoh, research in progress.